PHYSICAL BASIS FOR THE RADAR OBSERVATION OF GEOLOGICAL STRUCTURE IN THE ICE SHELL ON EUROPA. D.P. Winebrenner[1], D.D. Blankenship[2], B.A. Campbell[3], [1]University of Washington, Applied Physics Laboratory and Department of Earth and Space Sciences, Box 355640, Seattle, WA 98195 USA, dpw@apl.washington.edu, [2]Institute for Geophysics, University of Texas, Austin, TX 78759 USA, blank@ig.utexas.edu, [3]Center for Earth and Planetary Studies, Smithsonian Institution, Washington, DC 20560 USA, Campbellb@nasm.si.edu.

Introduction: Radar sounding of Europa has been discussed primarily as a means to measure the depth of a prospective ice/ocean interface [e.g. 1-4]. On terrestrial ice sheets, however, radar sounding commonly maps internal structure associated with compositional and structural horizons, i.e., by radar-reflective stratigraphic boundaries (depth variations of which encode information about ice dynamics and climate history).

Several types of radar-reflecting horizons other than an ice/ocean interface may occur on Europa [2-4]. In particular, where temperature varies in the transition between cold, brittle (impure) ice and warm, convecting ice, sharp dielectric contrasts will occur where temperatures pass through eutectic points of the impurities, thus creating a reflecting boundary [5]. Relict diapirs in cold (no-longer-convecting) ice [6], as well as buried crater floors [7], would differ sharply from surrounding ice in their bulk density and impurity content, thus also creating dielectric boundaries. Intermittent eruptions of low-viscosity material can create compositional, and thus dielectric, stratification wth depth. Finally, faults may be marked by discontinuities in density or crystallographic structure, which also translate to dielectric variations.

Understanding the surface expression of geological structure will be improved by tracking stratigraphic boundaries in the near-subsurface. Radar mapping of such boundaries may prove to be as important as the knowledge of ice thickness for understanding any interchange between the Europan surface and an underlying ocean.

These considerations motivate our examination of the dielectric properties of impure ice (Ih) at the low temperatures characteristic of Europa (75 to perhaps 250 K). We examine dielectric propertiesas function of temperature and of the concentrations of geologically plausible, dielectrically significant impurities. The latter include especially acid [8], chloride [2], subeutectic hydrated salts [1,2,9], and chondritic soils [1]. We focus initially on the effective conductivity, both because this property is fundamental to estimating how deeply radar can probe and because terrestrial experience suggests that conductivity variations may be the primary sources of reflection beneath the (poorly known [7]) annealing depth on Europa.

Effective Conductivity Due to Acid and Chloride Impurities: The effective conductivity of ice with ionic impurities, at typical radar sounding frequencies (tens of MHz), consists of a sum of contributions from resonances at much lower frequencies. The net effect at small impurity concentrations is a linear dependence of effective conductivity on each separate concentration, with coefficients, i.e., molar conductivities, which depend on temperature differently for each impurity via an Arrhenius relationship [2,10]. The dependence for a given impurity is smooth except at the eutectic temperature for that impurity – at the eutectic, the coefficient decreases abruptly with decreasing temperature, by a factor of 2-5 [3].

Figure 1 shows replotted data for molar conductivities of the two most dielectrically effective impurities, acid and chloride, assembled from various sources by Moore and Fujita [10]. The chloride data span two cases, one in which concentrations were below that where macroscopic brine pockets appear in the ice, the other above; they therefore bracket the range of possibilities at a given temperature. Also shown in figure 1 are extrapolations to Europan temperatures based on the pertinent Arrhenius relationship, with parameters determined by a fit to the data. The extrapolations are upper bounds on the true molar conductivities because the data from which they result were all acquired above the respective eutectics.

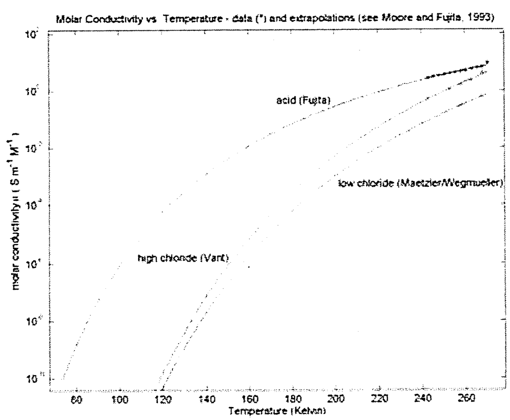

Figure 1. Semi-log plot of molar conductivity in Siemens per meter per mole versus temperature, according to tabulated data [8] and extrapolation. Data points are again denoted by asterisks, theoretical curves by solid lines. Legends on theoretical curves indicate first authors of papers in which the original data were presented.

The extrapolations indicate conductivities many orders of magnitude lower than those that occur in terrestrial ice environments. The required extrapolation far outside the range of observations, however, points up the need for new, low-temperature measurements [c.f., 1].

Effective Conductivity Due to Sub-Eutectic Salts or Chondritic Soils: Effective conductivities due to lunar or chondritic soil and to hydrated, sub-eutectic salts are much less well-known that those for ionic impurities. However, the synthesis of observations and empirical relations by Chyba et al. [1] strongly indicates that losses due to such impurities dominate those of ionic impurities at low temperatures, and that solid salt and soil impurities are roughly equivalent in their dielectric effects (see also [2]). Figure 2 shows one-way attenuation in dB/km for a radar sounding frequency of 50 MHz, and for effective conductivities derived as follows. For ionic impurities, we assumed, for purposes of illustration, equal volumetric concentrations of 300 micromoles per liter – concentrations close to or below those at which macroscopic brine or acid pockets appear. The acid and chloride curves in figure 2 are thus simply rescaled version of those in figure 1. For soil/salt impurities, we have tentatively adopted the density and empirical relations given by Chyba et al. [1] and assumed a volumetric concentration of impuritiesofl%.

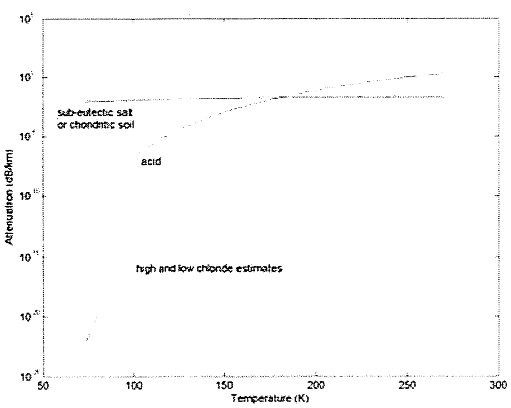

Figure 2. Semi-log plot of attenuation, in dB/km for various impurity species, using the fits in figure 1 with ionic species concentrations of 300 micromoles per liter, and the parameters and relations of Chyba et al. [1], assuming a volumetric impurity concentration of 1%.

The very low temperature sensitivity of conductivity in soil/salt impurities leads to their complete dominance of total dielectric loss at temperatures below ~180 K. While the relations given here must be regarded as very significantly uncertain, reversal of this latter conclusion would require that they be incorrect by many orders of magnitude.

Discussion: The computations in figures 1 and 2 must be regarded as significantly uncertain, given the range of extrapolation and scattered data on which they are based [1-3]. Our first conclusion is therefore that new observations are needed to narrow this uncertainty. However, even with the uncertainty, it seems clear that: (1) soil/salt impurities will dominate 50 MHz absorption at temperatures below about 180 K, which translates to more than half of the non-convecting ice thickness; (2) at higher temperatures, acid impurities quickly become dominant; (3) compostional radar horizons within upper half of the non-convecting ice will likely be caused by abrupt changes in soil or salt concentrations, the latter possibly derived from surface lag deposits – we will estimate the strength of such radar horizons based on the calculations presented here; and (5) because absorption is so low, we must consider limits on penetration depth due to scattering processes, both those due to stratication itself (i.e., 1-D inhomogeneities) and those due to scattering from 3-dimensional inhomogeneities and structure.

References:

[1] Chyba, C.F., Ostro, S.J., and Edwards, B.C., *Icarus 134,* 292-302. [2] Blankenship et al. (1999) University of Texas Institute of Geophysics, *Report No. 184.* [3] Moore, J.C. (2000) *Icarus 147,* 292-300. [4] Blankenship et al. (2001) *LPSC XXXII,* abstract 1854. [5] Matsuoka, T., Fujita, S., and Mae, S. (1997) *J. Phys. Chem. B 101,* 6219-6222. [6] Pappalardo, R. et al. (1998) *Nature 391*, 365-368. [7] Ostro, S.J., and E.M. Shoemaker. (1990) *Icarus 85*, 335-345. [8] Carlson, R.W, Johnson, R.E, and Anderson, M.S. (1999) *Science (286)*, 97-99. [9] McCord, T. et al. (1998) *Science 280*, 1242-1245. [10] Moore, J.C., and Fujita, S. (1993) *JGR 98,* 9767-9780.